minute from $LiOH+H^1$, CaF_2+H^1, and $B+H^1$, respectively. These results were secured under different experimental conditions for each target and indicate only the order of magnitude of the relative yields. Using an electroscope surrounded by 1 inch of lead, Hafstad and Tuve[13] found a ratio of ionizations of 0.13 for CaF_2+H^1 and $LiOH+H^1$. Observations made in this laboratory indicate a higher yield from CaF_2+H^1 relative to $B+H^1$ than the ratio of five to one indicated roughly by Bothe and Gentner's results. The yields found for $Li+H^1$ in this laboratory are not trustworthy as the composition of the surface of the target employed was uncertain. In all cases the observed yields must be corrected for the relative response of a counter or electroscope to incident quanta of different energies. In case the secondaries are produced in lead it can be shown that the response is roughly proportional to the energy of the quantum. The theoretical cross sections for pair formation and recoil electron production must be taken into account as well as the range of the pair and recoil secondaries. On this basis the yields from $LiOH+H^1$ and CaF_2+H^1 must be corrected by factors of ~ 2 and ~ 0.5 relative to that from $B+H^1$. The corrected yields are, respectively, 7×10^{-9} and 5×10^{-9} quanta per incident proton.

The yield for $LiOH+H^1$ is much larger than that given by the results of Hafstad, Heydenburg and Tuve, and the source of the discrepancy is not entirely clear. More direct evidence is obviously needed. Our results indicate a gamma-ray breadth of 40 volts for the 440 kv resonance for Li^7+H^1.

In conclusion it is well to point out that the radiative capture of protons by B^{11} is intimately connected with the alpha-particle transmutations occurring when boron is bombarded by protons. The $B^{11}+H^1$ reactions have been discussed by Kalckar, Oppenheimer and Serber,[14] but it is difficult to reconcile their conclusions simultaneously with the energy distribution of the gamma-radiation, with the large yield which we find and with other recent experimental results on these reactions. Further discussion of these difficulties will be found in this issue in an article by Professor Oppenheimer and Dr. Serber.

[14] Kalckar, Oppenheimer and Serber, Phys. Rev. **52**, 279 (1937).

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Note on Boron Plus Proton Reactions

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A discussion of the experimental evidence on the $B^{11}+H^1$ reactions and of the selection rules available for their interpretations shows that it is not possible to obtain a satisfactory description on the assumption that the same resonance level of C^{12} is responsible, both for the 16 Mev γ-ray observed by Fowler, Gaerttner and Lauritsen, and the long range alpha-particles whose angular distribution was determined by Neuert.

The disintegrations induced when B^{11} is bombarded with protons exhibit certain striking peculiarities. We wish to return to their interpretation in the light of new experimental evidence[1] on the yield and spectrum of the γ-rays observed in these reactions.

The essential findings may be briefly summarized. The most probable reaction involves[2] the emission of short range α-particles, leaving the Be^8 in an excited unstable state (probably ^1D). This reaction shows no resonance,[3] and is accompanied by no observable γ-rays or long range α's. Both the long range α's and the

[1] Fowler, Gaerttner and Lauritsen, Phys. Rev. **53**, 628 (1938).

[2] Dee and Gilbert, Proc. Roy. Soc. **154**, 279 (1936).

[3] Williams, Wells, Tate and Hill, Phys. Rev. **51**, 434 (1937).

γ-rays come from a resonance reaction.[4, 5] The resonance occurs at about 160 kv, and the resonance energy agrees within the experimental uncertainty of 2–3 kv for the two reactions.[6, 7]

Since for neither reaction has another resonance level been observed in the range up to 500 kv, it is natural to ascribe both reactions to the same level of the excited compound C^{12}. The resonance yield of α's from a pure B target is roughly 5×10^{-10};[3] the total yield of γ-rays determined by Fowler and Lauritsen[1] is also 5×10^{-10}.[8]

The long range α-particles are anisotropically distributed,[9] roughly according to a $1+\cos^2\theta$ law (with θ the angle between the direction of emission and the direction of bombardment). The γ-ray spectrum[1] shows three resoluble lines, at 4, 12 and 16 Mev. The first two have equal intensity; the 16 Mev line, which corresponds to transitions to normal C^{12}, is about six times as weak. Fowler and Lauritsen give arguments based on the excitation curves of Bothe and Gentner and their own work to make it plausible that all three γ-rays come from the 160 kv resonance.[1]

It is clear that for the interpretation of these findings selection rules will be essential. The known selection rules which could be invoked are these:

1. A compound nucleus cannot decay into products with vanishing intrinsic angular momentum if it has odd parity and even angular momentum, or even parity and odd angular momentum. This rule offers at first sight a natural explanation[10] of the absence of long range α's in the nonresonance reaction.

2. An odd C^{12} level of vanishing angular momentum can never give three α-particles. These rules, 1 and 2, are strict.

3. A triplet compound state will disintegrate to singlet products at a rate roughly 10^4 slower than a corresponding singlet, because the forces converting spin into orbital angular momentum are small. This argument is naturally invoked[10] to account for the great but not complete stability of the C^{12} resonance level to α-decay. Only singlet and triplet states may be expected when B^{11} is bombarded by protons.[11]

4. Since the Coulomb forces are still small for C, the isotopic spin[12] T may also be a fairly good quantum number, and a level of C^{12} with $T=1$ will disintegrate into products with $T=0$ at a rate reduced by a factor which may be of the order of 10^4 from that of levels with $T=0$. Only levels with $T=0$, 1 will be formed in the reactions considered.

No further relevant selection rules of comparable rigor would seem to follow from known invariance properties of the nuclear system.

The relatively large yield of short range α's shows that this reaction must come predominantly from the capture of s-protons, and the absence of observable resonance indicates that

[4] Bothe and Gentner, Zeits. f. Physik **104**, 685 (1937).

[5] Allen, Haxby and Williams, Phys. Rev. **53**, 325(A) (1938).

[6] We are indebted to Dr. Williams for a further discussion of the experimental results reported in reference 5.

[7] Allen, Haxby and Williams give 10 kv as the observed breadth of the resonance, but it seems (reference 6) not impossible that this is entirely instrumental, and comes primarily from the ripple and unsteadiness of the accelerating voltage of the protons. If one were to accept the observed breadth as real, it would add further serious difficulties to the interpretation; for since the proton breadth of the level must be very small compared to 10 kv, and since γ-radiation competes successfully with α-emission, this would necessitate a γ-ray breadth of the order of several kilovolts. This is larger than any value heretofore observed, and seems particularly implausible for radiation of magnetic dipole or electric quadripole type which, as we shall see, is probably involved in these reactions.

[8] The γ-ray yield is smaller than that from the Li^7+H^1 reaction by a factor of 10–20. If one accepts the absolute radiative field for the Li reaction given by Hafstad, Heydenburg and Tuve (Phys. Rev. **50**, 504 (1936)), one is led to γ-ray yields from the B reaction here considered which are about a tenth of those given by Fowler and Lauritsen. The precise value of the yield will not be important for our argument. In fact the γ-ray breadths of highly excited light nuclei are so difficult to estimate theoretically that our information about them must depend on just such absolute yield measurements as are here involved.

[9] Neuert, Physik. Zeits. **38**, 122 (1937).

[10] Kalckar, Oppenheimer and Serber, Phys. Rev. **52**, 279 (1937).

[11] In a recent letter Landau (Phys. Rev. **52**, 1251 (1937)) has objected to this argument, on the ground that the spin-orbit off-diagonal perturbation energy is not small compared to the spacing of the levels of a sufficiently highly excited sufficiently heavy nucleus. Quite apart from the fact that the "combining" resonance levels of C^{12} would seem to be spaced by several hundred kilovolts, this argument appears to involve a misapprehension, in that it uses an estimate of the magnitude of the matrix elements of the spin-orbit coupling energy based on a "one-body" model, of the level spacing based on a "many-body" model. It would in fact seem that the "average energy denominator" occurring in the perturbation theoretic treatment can hardly be essentially smaller than $\hbar$/collision time, and that the triplet contamination of a singlet wave function can hardly exceed a few percent. Analogous arguments apply to the selection rule 4.

[12] Wigner, Phys. Rev. **51**, 106 (1937). We are indebted to Professor Breit, who in private communications has emphasized the role which might be played by the so-called "partition quantum numbers."

singlet levels, with rapid α-decay rate and Γ_α breadths of the order of hundreds of kilovolts, must be involved. Since normal B^{11} is pretty certainly odd, 1 can be used to explain the absence of long range α's only if the C^{12} involved has even angular momentum; this cannot be zero by 2. We are thus led to assign for the normal state of B^{11} an odd D, G term. The most plausible state seems to be a $^2D_{3/2}$.

The angular dependence of the long range α's shows that the resonance level is formed not by s, but by p or d proton capture. Estimates of the proton breadth, based on correcting the observed breadth of the 440 kv resonance level in the Li^7+H^1 reaction for altered barrier penetrability, give $\Gamma_p \sim 5$ v for p-protons, and about 1/100 of that for d-protons. The observed resonance yields thus show that we have to do with p-capture, and that the minimum possible value for γ-ray and long range α breadth is of the same order as the proton breadth. Since $\Gamma_\alpha < 10\Gamma_\gamma$, it is hard to accept the "observed" breadth of the resonance level, ~ 10 kv, as real.

The resonance level is then even; its angular momentum i must be 1 or 2, since it gives γ-rays to ^1S of normal C^{12}; and since it gives long range α's we must have $i=2$. The resonance level must therefore be a ^1D, or a $^3P_2$, $^3D_2$, or $^3F_2$. Now the energy[13] of the resonance level differs from that of normal B^{12} by just about what we should expect for the Coulomb energy difference (~ 0.002 mu). Since the normal state of B^{12} is the lowest lying term of isotopic spin $T=1$, we should expect[14] the resonance level to be a singlet or triplet P, D or F with $T=1$. The great stability of the level to α-decay would suggest that it is a triplet, so that selection rules 3 and 4 could both be invoked to explain this stability. Since however an even pure triplet $^3P_2$, $^3D_2$, $^3F_2$, cannot combine with the ^1S normal state of C^{12} by γ-radiation, this possibility is excluded. In fact the only triplet which could give the high energy γ-ray with the observed intensity is an even ^3S, which can neither give long range α's nor be formed from a parent B^{11} in a ^2D state by p capture.

The only remaining possibility is that the resonance level is an even ^1D with $T=1$, and that its stability must be understood in terms of the approximate conservation law for isotopic spin. However the angular distribution to be expected for the long range α's, for p capture to ^1D from a $^2D_{3/2,\,5/2}$ parent term of B^{11}, is $\sin^2\theta$, which cannot be reconciled with the observed $1+\cos^2\theta$. It will be seen from Table I that, to obtain an anisotropy even qualitatively in agreement with experiment, we would be forced either to make the resonance level a ^3F, or to make the parent term one of odd L and thus to give up the explanation, in terms of the parity angular momentum selection rule, of the striking absence of long range α's in the dominant s capture reaction.

We have been led to this very unsatisfactory conclusion by the supposition that both the long range α-particles and the 16 Mev γ-rays come from the same resonance level. In this connection it should be emphasized that the yields of long range α-particles and γ-rays have not been adequately investigated in the range above 250 kv. If one assumes, as our arguments perhaps suggest, that the high energy γ-ray comes from a resonance level in this range, and other than that for which the angular distribution of the long range α's has been determined, no unique assignment of the resonance level is possible at present. If this should turn out to be true, one would probably still have some difficulty in reconciling a ^2D parent B with a triplet character for the resonance level.

TABLE I. *Angular distribution of long range α-particles.* $c=\cos\theta$, $s=\sin\theta$.

RESONANCE STATE OF C^{12}	NORMAL STATE OF B^{11}				
	$^2P_{1/2}$	$^2P_{3/2}$	$^2D_{3/2}$	$^2D_{5/2}$	$^2F_{5/2,\,7/2}$
^1D	$1+3c^2$	$1+3c^2$	s^2	s^2	$2+c^2$
$^3P_2$	$1+3c^2$	$1+6s^2$	$1+6s^2$	$3+c^2$	
$^3D_2$	$1+3c^2$	1	$3+4s^2$	$4+7s^2$	
$^3F_2$			$1+2c^2$	$1+16s^2$	
$^3F_4$				$3+5c^2$	

[13] We wish to thank Professor Breit for pointing out to us the possible homology of the resonance level and normal B^{12}.

[14] Feenberg and Phillips, Phys. Rev. **51**, 597 (1937).